

Confronting Synchrotron Shock and Inverse Comptonization Models with GRB Spectral Evolution

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Abstract. The time-resolved spectra of gamma-ray bursts (GRBs) remain in conflict with many proposed models for these events. After proving that most of the bursts in our sample show evidence for spectral “shape-shifting”, we discuss what restrictions that BATSE time-resolved burst spectra place on current models. We find that the synchrotron shock model does not allow for the steep low-energy spectral slope observed in many bursts, including GRB 970111. We also determine that saturated Comptonization with *only* Thomson thinning fails to explain the observed rise and fall of the low-energy spectral slope seen in GRB 970111 and other bursts. This implies that saturated Comptonization models must include some mechanism which can cause the Thomson depth to increase initially in pulses.

INTRODUCTION

While observations of gamma-ray burst counterparts appear to have determined the distance scale of these enigmatic events [1], questions regarding the emission mechanism remain unanswered. Models are tested against the newly discovered X-ray and optical power-law tails seen in two GRBs [2,3], however most of these were flexible enough to accommodate the observations. Multiple gamma-ray emission mechanisms have also been found to be consistent with the *time-integrated* spectra making this another poor test of GRB models.

In order to evaluate GRB models, we look to the time evolution of GRB spectra. Most spectral evolution studies have looked only at the evolution of spectral hardness, which has historically been represented by either a hardness ratio or by the peak of the $\nu F\nu$ spectrum, E_{peak} [4]. We examine this as well as the evolution of the low-energy asymptotic slope α (as defined by the Band GRB function [5]). In the following section, we show that most bursts require evolution of this second parameter. Thus the shape, as well as the break energy, of the spectra evolves as a function of time. Models which were consistent with the time-integrated spectra can be inconsistent with the time-resolved spectra. Below we confront first the synchrotron

shock model and then the inverse Comptonization model with our time-resolved BATSE burst spectra. We find that both models are currently unable to explain our observations.

I SPECTRAL SHAPE-SHIFTING BURSTS

We first demonstrate that time-integrated burst spectra do not well represent the time-resolved spectra. Previously we have found that a minimum first-order trend in α is shown to exist in at least 46 of the 79 bursts we analyzed [6]. It is possible that some higher order evolution of α may occur in these bursts. To test for this, we calculated the χ^2 between the time-resolved, fitted values of α and the weighted average value of α in each burst. We found that only 30 out of the 79 bursts are consistent with an invariant α , assuming $Q(\chi^2) > 0.001$ as an acceptable cutoff [7]. We conclude that the remaining 63% of the bursts have a varying α , consistent with the results of [6]. Unfortunately, time-resolved β values are poorly determined in a majority of the bursts in this sample.

As an example of spectral shape-shifting in GRBs, we examine the early evolution of GRB 970111 (see Figure 1). We find the first several seconds to be remarkably similar to GRB 910927 (see Figure 1 of [6]). Both bursts exhibit steep *positive* low-energy power slopes. Fitting the Band GRB function [5] to GRB 970111, we find $\alpha_{\text{max}} = +1.5 \pm 0.2$, a value consistent with the maximum α in GRB 910927. We would expect this value of α from synchrotron self-absorption. However, with synchrotron self-absorption, α is either $+\frac{3}{2}$ in the case of a nonthermal plasma or $+1$ for a thermal plasma [8]. This mechanism cannot produce the variation of observed α values.

II SYNCHROTRON SHOCK MODEL

One prediction of synchrotron shock models is easily tested with GRB spectral data. For these models, the asymptotic low-energy photon slope α (below the spectral break) should be between $-\frac{2}{3}$, in the case of an instantaneous synchrotron spectrum, and $-\frac{3}{2}$, when the spectrum is integrated over the radiative decay of electron energies [9]. These predictions are tested by Cohen et al. [9] with 11 *time-integrated* GRBs. In these 11 cases, the slope of the low-energy spectra is indeed in this range. However, time-resolved spectra reported in Crider et al. [6] clearly show evidence for GRB spectra which cannot be explained with this mechanism. Examination of a larger set of bursts show that many bursts have maximum α values beyond the “line-of-death” ($\alpha > -\frac{2}{3}$) predicted by synchrotron shock models [10].

To evaluate the synchrotron shock model quantitatively, we began by finding the probabilities Q of randomly getting poorer χ^2 values when fitting the Band GRB function [5] to time bins selected from GRB 910807, GRB 910927, and GRB 931126. These are respectively 0.93, 0.50, and 0.25 suggesting that the Band et al. function [5] adequately describes the observed spectra. When we instead fixed

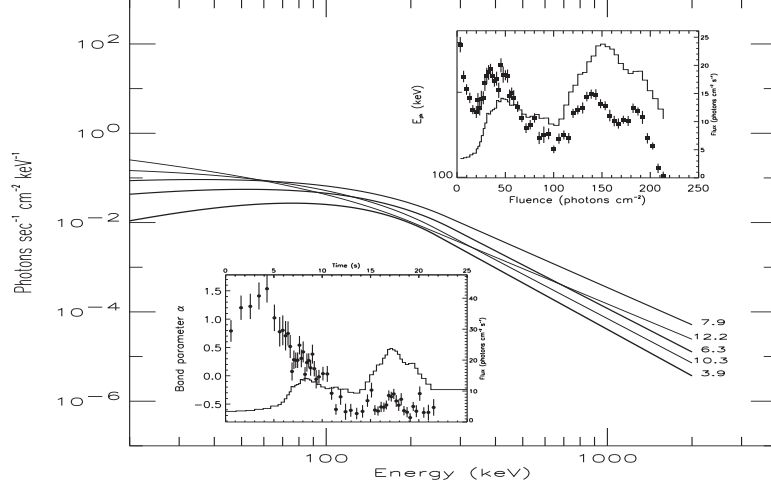


FIGURE 1. Evolution of the Band *et al.* GRB spectral function for 3B 970111. Each line is marked with the time (in s) corresponding to the beginning of the time bin. Note that a typical statistical β error $\sigma_\beta \approx 0.6$. [Upper inset] Evolution of E_{peak} (squares, logarithmic scale) and photon flux (histogram, linear scale) with respect to fluence. [Lower inset] Evolution of α (circles) and photon flux (histogram) with respect to time. Error bars represent 1σ confidence level. The early initial values and evolution of α in this burst are difficult to reconcile with the synchrotron shock model.

$\alpha = -\frac{2}{3}$ to represent the maximum slope allowed by synchrotron shock models, we found Q values of 5×10^{-5} , 1.5×10^{-11} , and 7×10^{-11} , which makes this model unacceptable in explaining the data. Also, when fitting the time bin in GRB 970111 where $\alpha = +1.5 \pm 0.2$ gave $Q=0.32$ for the Band *et al.* function compared to $Q=8.5 \times 10^{-21}$ when α is fixed to $-\frac{2}{3}$. Three sample spectra from these bursts are plotted in Figure 2 in a fashion similar to that of Cohen *et al.* [9] where the limits of the synchrotron shock model are overlayed onto the deconvolved burst spectra. This figure clearly shows that these bursts' spectral slopes are outside the range predicted by the synchrotron shock model.

III SATURATED COMPTONIZATION MODEL

The generally decreasing nature of α from values approaching +2 is suggestive of saturated inverse Compton scattering in a plasma experiencing Thomson thinning [6,11]. However, many bursts show some evidence for an *increase* in α at the beginning of pulses which would represent a Thomson thickening. The observed changes in α cannot be attributed to statistical fluctuations or systematics. GRB 950818 is an excellent example. To show more clearly how the Thomson depth τ_T evolves in this burst, we fit it with the Sunyaev-Titarchuk model. The evolution of τ determined from these fits is shown in Figure 3. While this model does not often fit gamma-ray bursts well, fits with the Band GRB function [5] and comparisons

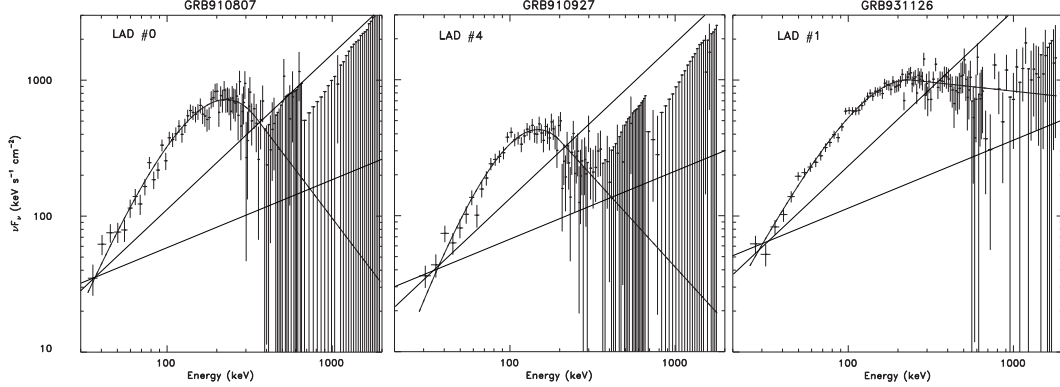


FIGURE 2. Spectra from GRB 910807, GRB 910927, and GRB 931126 for the time bin in each where the maximum steepness in the low-energy slope occurred. The fitted α for these are, from left to right, $+1.1 \pm 0.3$, $+1.6 \pm 0.3$, and $+0.4 \pm 0.1$. Also plotted are the limits between which the low-energy asymptotic slope should be for the synchrotron shock model ($-\frac{2}{3} \geq \alpha \geq -\frac{3}{2}$). The observed slopes are clearly inconsistent with the synchrotron shock predictions.

with our simulated inverse Compton spectra [11] indicate that the spectral break is always below 100 keV and that τ_T should be ~ 4 . In this parameter space, the Sunyaev-Titarchuk model is appropriate if we ignore data above the spectral break which will be heavily influenced by any non-thermal component. The results of fitting this model to our data appear in the figure above and show that τ_T clearly increases and then falls during this burst. One means by which τ_T may rise and fall would be an initial compression of the plasma. Future research will test if this is a valid hypothesis.

IV DISCUSSION

We have found that most bursts show some degree of spectral “shape-shifting” making the time-integrated spectrum an inadequate diagnostic of gamma-ray burst models. The high value of the low-energy spectral slope $\alpha \sim +1.5$ seen in some bursts and the flattening of this slope with time is incompatible with the synchrotron shock model. Similarly, simple Thomson thinning from an initial state of saturated Comptonization cannot explain the rise and fall of α seen in some bursts. It may be possible to reproduce the observed spectra with a changing superposition of self-absorbed synchrotron spectra. However this has not yet been explored in detail within the construct of the blast-wave scenario.

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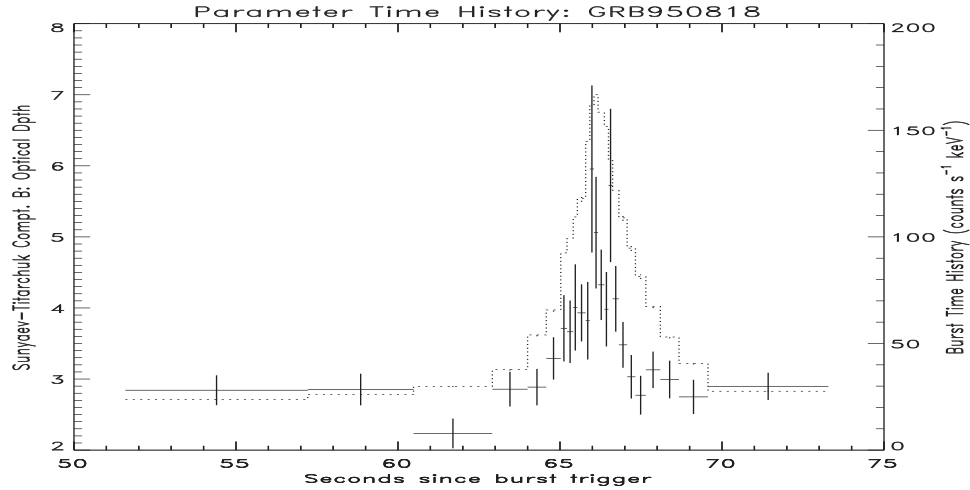


FIGURE 3. The evolution of the Sunyaev-Titarchuk Thomson depth τ_T (crosses) and photon flux (histogram) with time for GRB 950818. These points are from fits to the 30-300 keV BATSE LAD spectra. This evolution of τ_T is difficult to reconcile with a simple Thomson thinning model.

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